Physical Layer Performance of Multi-User Detection in Broadband Multi-Beam Systems based on DVB-S2

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***Abstract*—In this paper we investigate the physical layer performance that can be obtained in a DVB-S2-based broadband system when high frequency reuse is applied and Multi-User Detection (MUD) is adopted at the receiver side to cope with the presence of interference. By calculating the Bit Error Rate (BER) which results from the application of MUD in various cases, the sensitivity of the algorithm to the signals' parameters is first assessed. Then, we show that by jointly detecting/decoding the useful signal and the interferers the peak data rate of the users affected by strong co-channel interference can be significantly increased.**

I. Introduction

In recent years, the need to support a wide range of broadband services and to satisfy the growing demand for high data rates pushed the development of many techniques and technologies in order to increase the overall system spectral efficiency. The second-generation specification of the digital video broadcasting for satellite (DVB-S2) [1] was developed in 2003 with the main aim of improving the system performance with a reasonable receiver complexity. Ten years after, the DVB project has defined an evolution of DVB-S2[2] [3], with the aim of further improving the system flexibility and efficiency without significantly increasing the receiver complexity.

The adoption of multi-beam system architecture is essential for achieving higher data rates as the aggregated capacity increases thanks to the possibility to re-use the frequency in many beams. In this paper, we consider the forward link of these systems, where the users across the coverage area access the available resources via time division multiplexing (TDM) and frequency reuse is applied. As the capacity increases linearly with the available bandwidth per beam, it would be desirable to re-use as much as possible the available bandwidth among the beams, for example with a frequency reuse factor of 2 or even 1. In such systems the interference caused by the secondary lobes of the closest beams may represent a severe limitation to the link quality—when such an aggressive frequency reuse is applied, co-channel interference represents indeed the limiting factor for the overall signal-to-noise-plus-interference (SNIR) ratio. Interference mitigation (IM) techniques target the partial or total removal of the intra-system interference with the aim of improving the link SNIR and consequently the resulting spectral efficiency. Within this family, optimal or suboptimal multi-user detection (MUD) techniques play certainly a major role, although an increased computational complexity is required at the receiver—this is, however, a minor problem due to the computational power available nowadays compared to 2003.

This paper focuses on the adoption of IM techniques at the terminal side in a DVB-S2 system and presents an assessment on the physical layer performance of a specific MUD algorithm, giving an insight on the behaviour of the algorithm in various scenarios and assessing its capabilities to increase the user peak rate when high co-channel interference is experienced.

In the following, Section II presents the reference system model, Section III discusses in general the interference mitigation techniques, while Section IV discusses the

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approach based on MUD. Numerical results are presented in Section V, whereas conclusions are drawn in Section VI.

II. SYSTEM MODEL

A. Radio interface

We consider a downlink DVB-S2 system with B beams [1]. The transmitted signal intended for the ℓ-th beam can be written as

$$s_\ell(t) = \sqrt{E_\ell} \sum_{k=1}^{L_F} x_k^{(\ell)} g(t - kT_s) \quad (1)$$

where E_ℓ is the ℓ-th signal energy, L_F is the length of the frame, $x_k^{(\ell)}$ are complex symbols drawn from either PSK (phase shift keying) or APSK (amplitude-phase shift keying) constellations, and can be either data or pilot symbols, $g(t)$ is the square-root-raised-cosine pulse shaping filter, and T_s is the symbol time.

Each user will receive the superposition of several signals, due to the overlap of the footprint of the beams, and the signals will not be totally synchronous, due to the slight inaccuracies of the clocks of the ground station and the satellite. In formulas, the received signal by a generic user after frequency down-conversion can be written as

$$r(t) = \mathrm{e}^{\jmath(2\pi f_e t + \theta(t))} \sum_{\ell=1}^{B} \alpha_\ell s_\ell(t - \tau_\ell) \mathrm{e}^{\jmath(2\pi f_\ell t + \theta_\ell)} + w(t) \quad (2)$$

where f_e and $\theta(t)$ are the frequency error and the phase noise of the receive front-end[1], α_ℓ is the complex channel gain of the ℓ-th signal, which is received with a delay τ_ℓ, a frequency offset f_ℓ and a phase offset θ_ℓ. The noise process is represented by $w(t)$, a complex Gaussian process with two-sided power spectral denstity $2N_0$.

B. Reference System scenario

We describe now the reference system scenario used in our investigation. It is assumed that the detection algorithm is aware of the modulation and coding formats (modcods) employed by the reference users and the most relevant interferers and that their power (i.e. signal-to-noise ratio and interference power) can be estimated by the receiver. Once these parameters are known, the physical layer simulations provide then the trend of the bit-error-rate (BER) for each modcod as a function of the ratio C/N of the link, where C is the average received power and N is the noise power in the bandwidth assigned to each signal. Summarizing, for the application of MUD the following figures related to a single user forward down-link play a key role:

$$\left(\frac{C}{N}\right), \left(\frac{C}{I_i}\right), \quad \text{with} \quad i = 1 \ldots N_{co-ch} \quad \text{and} \quad I_i > I_{i+1} \quad (3)$$

where N_{co-ch} is the number of co-channel beams, i.e., co-channel interfering signals received by the considered user and I_i is the power received from the i-th interfering beam. Consequently I_1 is the strongest interference contribution, I_2 the second strongest one and so on. As can be deduced, each modcod requires a different C/N threshold depending on the values of the C/I_i of the main interferers.

In order to carry out the assessment of the proposed algorithm, a standard multi-beam system scenario with -3 dB crossover has been considered as a reference. The baseline scenario assumes the DVB-S2 standard air interface and modcods and applies therefore adaptive coding and modulation (ACM). Intuitively, the MUD performs better where high interference is present, which lead us to choose a frequency reuse with factor 2. This choice is the result of a compromise between user link bandwidth and the interference levels manageable by the algorithms: a full frequency reuse scheme would imply not only a lower total C/I but a higher number of significant signals to be decoded and therefore a higher complexity of the user terminal. From a sensitivity assessment on the distribution of the various C/I_i and on their correlation, it appears that a certain correlation between the C/I_1 and the remaining C/I_i, $i > 1$ is present over the coverage. Among the various interference values, it is then possible to identify the set of cases defined in Table I, which are representative of a large number of users mostly located close to the edge of coverage of a beam of the considered system.

TABLE I. TABLE OF THE CONSIDERED C/I CASES

Case	C/I_1	C/I_2	C/I_3	C/I_4	C/I_5
1	0	25	25	27	30
2	2	26	26	27	30
3	4	27	26	27	30

III. IM AT THE TERMINAL: THEORETICAL ANALYSIS

In this study, IM approaches at the user terminal side are considered, i.e., at the receiver side of the forward link of satellite communication systems. IM has the objective of reducing the impact of co-channel interference on the desired signal. Although the addressed techniques are those already developed for the multiple-access channel, the difference in the final objective (reducing the impact of the interfering vs. maximizing the sum-rate capacity) brings into the picture several elements that shall be carefully considered in the study. In particular, we underline from the very beginning that contrary to the conventional MUD approaches, decoding all of the received signals is not a target, but just a tool to improve the decodability of the reference/wanted signal for the specific user under consideration. As we will discuss in Section III-A this has important consequences on the applicability and performance of MUD at the terminal side.

A. Gaussian Interferer Model and Validation

In order to speculate on the possible behavior of the system in the considered scenario, we introduce in this section a theoretical model based on the assumption that noise plus interferers can be approximated as a Gaussian process, which is usually verified for several numbers of interferers. In order to empirically validate this assumption, Figure 1 reports histograms of the signal plus interferer plus noise amplitude for Case 1 C/I analysis and E_s/N_0=5 dB, (where E_s is the energy per symbol of the reference user) which corresponds

[1]We assume that the phase noise effects are located at the receiver side, due to the fact that the receiver's oscillators are of mass-market quality, while ground station and payload circuitry have a very high quality.

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to C/N=4.6 dB using $\beta = 0.1$. From the figure, it is clear that noise plus interference distribution matches fairly well a Gaussian distribution for the considered case.

It is worth noting that the Gaussian approximation is even more valid for low and medium signal-to-noise ratio (SNR) values.

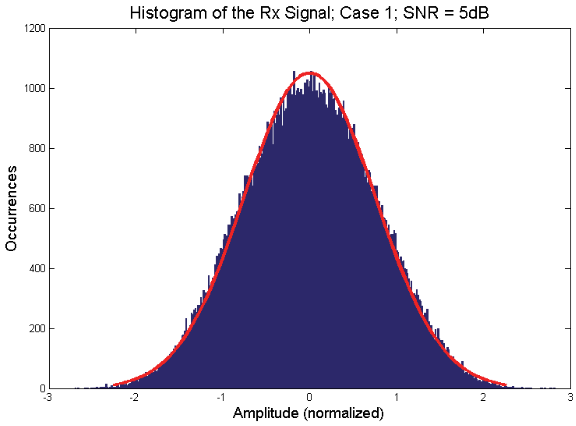

Fig. 1. Histograms plot for signal plus interferer plus noise

The Gaussian approximation permits us to derive new decoding thresholds for DVB-S2 modcods for the considered interference scenarios. Figure 2 should be interpreted as follow: considering a DVB-S2 receiver without any IM technique, if a particular curve is able to exceed one of the DVB-S2 decoding thresholds then the receiver is also able to decode. On the contrary, if a curve remains under the threshold, the corresponding receiver cannot decode. Decoding thresholds for QPSK 1/4, 2/5, 1/2, 3/5, 3/4 and for 8PSK 3/5, 3/4, 5/6, 8/9 are reported in black. Dark blue curves are the SNIR behaviours obtained for the considered case analysis while light blue curves (which are superimposed in figure) are the one ideally obtained in case the first interferer could be cancelled.

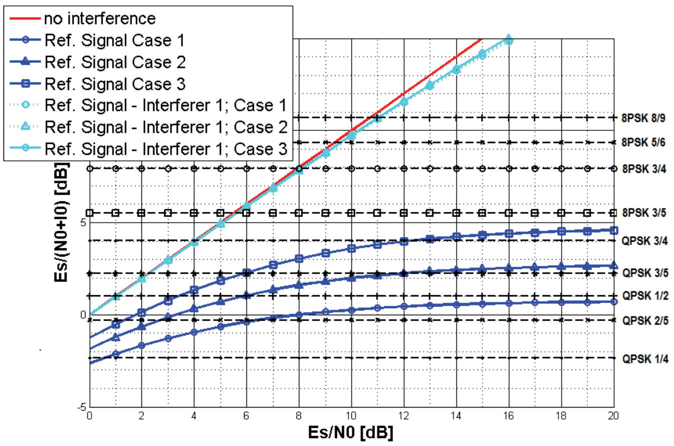

Fig. 2. $E_s/(N_0 + I_0)$ analysis for Case 1, Case 2 and Case 3, where I_0 is given by the sum of all interferers power

The model crearly shows that, using a single-user detector/decoder, the highest spectrally efficient modcod to be used is QPSK 2/5 modcod which is able to decode at $E_s/N_0 \simeq 6.5$ dB for Case 1, which corresponds to $C/N \simeq 6$ dB. For Case 2, QPSK 3/5 is the highest spectrally efficient modcod able to decode at $E_s/N_0 \simeq 12$ dB while for Case 3, QPSK 3/4 is the highest spectrally efficient modcod able to decode at $E_s/N_0 \simeq 12$ dB, which both correspond to $C/N \simeq 11.6$ dB. A comparison between DVB-S2 decoding thresholds in AWGN and with co-channel interference (Figure 2) shows a loss of about 7 dB for Case 1, a loss of about 9.5 dB for Case 2 and a loss of about 8 dB for Case 3 which justifies the use of IM techniques.

IM at the user terminal differs from classical IM at the gateway, because the interest is just on a single signal (i.e., the reference signal), which in general is also the strongest one, and not necessarily to the entire set of received signals. Hence, in case of SIC, in which the strongest signal has to be decoded first, the process stops when the reference signal decodes. This means that it is likely that some interferers might never be decoded in some scenarios, because the reference signal always decodes first. Hence, they are to be considered as "undecodable/undetectable", i.e., background noise, which cannot be exploited for processing. In addition, since for cancellation it is required that the signal to be cancelled decodes quasi-error free, it is likely for SIC to be unfeasible.

From the Gaussian model in Figure 2, a preliminary analysis on the use of successive interference cancellation (SIC) can be intuitively sketched as follows. For example, let us consider Case 1 C/I values, in which the reference signal and the first interferer have the same power and let us assume the same modcod for the reference signal and interferers. In case of SIC for Case 1 we could try to cancel the first interferer and then decode the reference signal while for Case 2 and Case 3 it is not possible because, as explained, the strongest signal is the reference signal. The most efficient modcod that could be decoded for Case 1 is the QPSK 2/5 which requires a SNR value of about 6.5 dB (see Figure 2) . If quasi-error free decoding is attained and the interfering signal is cancelled, then the reference signal SNR behaviour becomes represented by the light blue curve. However, since the selected modcod is the QPSK 2/5 for both reference signal and interferers, the SNR improvement cannot be translated in a spectral efficiency improvement, hence the use of SIC provides no advantage in this scenario.

Due to the previous considerations, optimal MUD [4] techniques are attractive and complexity could be limited in some scenario where the number of detectable interferers is small.

IV. Multi User Detection

The aim of this paper is to evaluate the possible gains that can be obtained through an increased frequency reuse and the adoption of more sophisticated processing techniques at the receiver. Thus, for simplicity, the signals of different beams are assumed to adopt the same base pulse and symbol time, to be co-frequency and perfectly aligned in time. Synchronization is assumed perfect, and also nonlinear channel distortions are assumed to be negligible. Hence, at the receiver, the samples at the output of a filter matched to a base pulse can be expressed

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as[2]

$$r_k = \sum_{\ell=1}^{B} \alpha_\ell x_k^{(\ell)} e^{\jmath\theta_k^{(\ell)}} + w_k \tag{4}$$

where $x_k^{(\ell)}$ is the $M^{(\ell)}$-ary symbol sent over the ℓth beam at discrete time k, assumed to include also the energy factor in (1) to simplify the notation, α_ℓ is its attenuation, assumed constant over an entire codeword, $\theta_k^{(\ell)}$ is its time-varying phase shift, and $\{w_k\}$ is a discrete-time complex white Gaussian noise process with zero mean and variance $\sigma^2 = N_0$ per component. Without loss of generality, we will assume that $\alpha_\ell \geq \alpha_{\ell+1}$ and that the reference signal is that for $\ell = 1$. As mentioned, synchronization is assumed perfect and thus the attenuations and the phase shifts are perfectly known at the receiver. At the receiver, we adopt the optimal MUD, under the assumption that only the U more powerful signals are present. In other words, the optimal detector for the following auxiliary channel is considered:

$$r_k = \sum_{\ell=1}^{U} \alpha_\ell x_k^{(\ell)} e^{\jmath\theta_k^{(\ell)}} + w'_k \tag{5}$$

where $U = 2$ or 3, and $w'_k = w_k + \sum_{\ell=U+1}^{B} \alpha_\ell x_k^{(\ell)} e^{\jmath\theta_k^{(\ell)}}$ is still assumed to be AWGN with variance δ^2 per component. Hence, according to the auxiliary channel model it is

$$p(r_k|x_k^{(1)}, \ldots, x_k^{(U)}) = \frac{1}{2\pi\delta^2} \exp\left\{ -\frac{\left| r_k - \sum_{\ell=1}^{U} \alpha_\ell x_k^{(\ell)} e^{\jmath\theta_k^{(\ell)}} \right|^2}{2\delta^2} \right\}$$

and thus, through an average of all symbols but $x_k^{(\ell)}$, taking into account the soft information provided by the outer decoders, the extrinsic information $p(r_k|x_k^{(\ell)})$ for all U users is computed and exchanged with the corresponding decoders. The detector complexity is clearly proportional to the product $M^{(1)} \cdot M^{(2)} \cdot \ldots \cdot M^{(U)}$.

When the above mentioned assumption on perfect synchronization does not hold, obviously a degradation has to be expected. The evaluation of the robustness of this receiver to synchronization errors and the investigation of proper synchronization techniques is left to a further investigation. Instead, the assumption on perfect alignment in time or frequency of interfering signals is not critical. In fact, we evaluated the performance degradation occurring for a time misalignment of $T/10$ or a frequency misalignment of 5% of the baud rate, observing a negligible performance degradation. However, it has to be considered that, when a larger time misalignment occurs, the system can no longer be considered memoryless and the detector complexity increases. Techniques for reduced-complexity MUD has to be thus considered (as an example, see [5] and references therein).

V. Numerical Results

As discussed in the previous sections, the physical layer performance of the MUD algorithm are heavily impacted by the number of users U to be detected and decoded (e.g., if $U = 3$, the reference signal plus the first two strongest interferers are detected) and the C/I_i, $i > 1$ measured on each link. Following this consideration, the results here presented provide an assessment on the behaviour of MUD as function of these variables. For complexity reasons, it is assumed to have the same modulation order on both the reference signal and the interfering signal and that the rate 3/5 is applied to the interfering signal. Figure 3 shows an example of BER curves obtained for Case 1 and $U = 3$, assuming that the interferer operates with a rate 3/5; similarly, a set of BER curves can be obtained for each case and for $U = 2$.

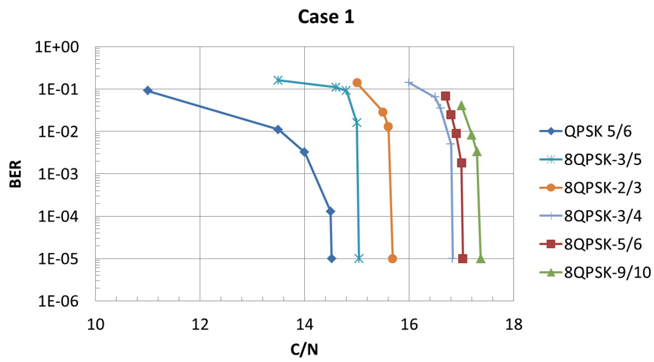

Fig. 3. BER curves obtained for Case 1 using MUD for 3 signals

It is worth to start the analysis from the sensitivity on the number of detected users U: the following results assume to apply the algorithm detecting 2 or 3 users, namely MUD for 2 or MUD for 3. Figure 4 compares the C/N thresholds required by each modcod to have a BER of 10^{-5}.

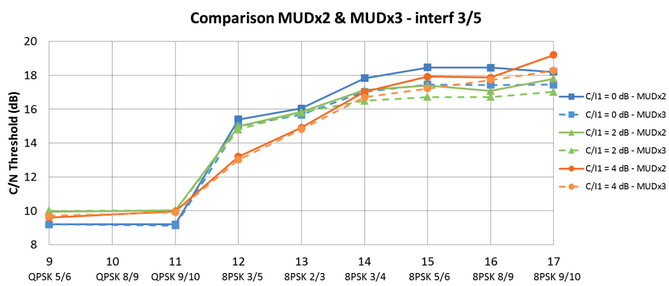

Fig. 4. C/N thresholds comparison between MUD for 2 signals and MUD for 3 signals. Same modulation order has been considered for the interfering and the useful signal

As expected, the detection of 3 users gives slightly better results. MUD for 2 has almost the same threshold up to 8PSK 2/3 and then MUD for 3 gains between 0.5 up to 1 dB of decoding threshold. However, this difference might not be enough to justify the increase of complexity that would be required to carry out the detection of 3 signals. In fact, looking again at Table I it is possible to deduce that being the C/I_i quite high, there is no actual need to detect and decode I_2. With regards to the C/I_1, it can be highlighted that the thresholds tend to increase proportionally to I_1/C up to 8PSK 2/3, while for higher modcods the thresholds seem to increase with higher C/I_1.

[2]The base pulses used in DVB-S2 transmissions are such the condition for the absence of intersymbol interference is satisfied.

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TABLE II. LINK BUDGET FOR CASE 1, CASE 2, AND CASE 3

SYSTEM PARAMETERS	CASE 1	CASE 2	CASE 3	Unit
Satellite location	13E	13E	13E	deg
Up-Link frequency:	30	30	30	GHz
Carrier Symbol Rate:	454.55	454.55	454.55	Mbaud
Roll-off:	0.1	0.1	0.1	
Carrier Bandwidth:	500	500	500	MHz
User Link Beam Bandwidth:	500	500	500	MHz
Down-Link frequency:	20	20	20	GHz
UPLINK				
UL Es/(N0+I0):	19.99	19.99	19.99	dB
SAT TX				
Satellite Saturated Output Power:	65	65	65	W
Sat TX OBO:	1.43	1.43	1.43	dB
Sat TX Losses (total):	2.05	2.05	2.05	dB
EIRP per carrier:	69.93	68.7	71.2	dB
Total Atmospheric Losses:	0.63	0.66	0.67	dB
Propagation Losses:	210.08	210.09	210.07	dB
Down link polarization Losses :	0.2	0.2	0.2	dB
TERMINAL RX				
Latitude:	46	46.5	45.2	deg
Longitude:	3.25	3	1.75	deg
Terminal RX G/T:	16.26	16.26	16.26	dB/K
Terminal RX Losses :	0.7	0.7	0.7	dB
DL C/N:	16.96	15.7	18.2	dB
DL Total C/I:	0.33	2.22	4.21	dB
Total $E_s/(N_0+I_0)$:	0.26	2.1	4.05	dB
ACM				
ACM Selected Modcod:	QPSK 1/3	QPSK 1/2	QPSK 2/3	
ACM Spectral Efficiency:	0.67	1	1.33	bit/symb
MUD + ACM Selected Modcod:	8PSK 2/3	8PSK 3/5	8PSK 3/4	
MUD + ACM Spectral Efficiency	2	1.8	2.25	bit/symb

To complete this analysis, we propose hereby three examples of a link budget for three specific points, each related to the considered Cases 1÷3 and to the consequent gain in spectral efficiency that could be achieved with the application of MUD on top of ACM. Table II shows that, for the selected examples, the application of MUD for 2 signals on top of ACM allows to significantly increase the spectral efficiency with respect to the simple application of ACM with DVB-S2 thresholds. Especially for the case in which the strongest interferer has power similar to the main signal, the spectral efficiency can be in fact increased from 0.67 up to 2 bit/symb. Finally, it is worth noting that while for standard ACM the performance are driven by the total $E_s/(N_0 + I_0)$, for what concerns ACM together with MUD, the spectral efficiency is uniquely determined by the C/N.

VI. CONCLUSIONS AND FUTURE WORK

In this paper we have carried out an assessment on the physical layer results achievable with a specific algorithm for MUD, showing that the detection of two users might be sufficient to increase substantially the spectral efficiency of the link. This is true most of all for the users experiencing high level of co-channel interference, which are usually located close to the edge of the beam. It is worth however to note that it is expected that for other users in the coverage, the achievable gain decreases for increasing C/I_1, reducing the overall gain of the MUD technique. Nevertheless, the results shown in this paper provide a good evidence that advanced interference mitigation techniques can be effective in improving the data rates of users affected by high intra-system interference.

Future investigations are required to detail performance evaluation at system level, with the support of theoretical capacity analysis.

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